QUANTIFYING BIODIVERSITY VALUES ACROSS MANAGED LANDSCAPES IN NORTHERN AND WESTERN MAINE

Erin Simons, Daniel Harrison,
Andrew Whitman and Jeremy Wilson

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Erin Simons, Assistant Scientist, Department of Wildlife Ecology and Center for Research on Sustainable Forests, University of Maine.

Daniel Harrison, Professor of Wildlife Ecology, Cooperating Scientist with Maine Cooperative Forestry Research Unit, Cooperating Professor, Center for Research on Sustainable Forests, University of Maine.

Andrew Whitman, Director of Natural Capital Initiative, Manomet Center for Conservation Sciences.

Jeremy Wilson, Associate Professor of Forest Resources and Irving Chair for Forest Ecosystem Management, University of Maine.

INTRODUCTION

Commercial forest landowners are expected to address the habitat needs of wildlife and plant species in an effort to maintain viable populations of species across commercially managed landscapes. Landowners who participate in forest certification are required to monitor and maintain forest biodiversity. Unfortunately, they lack tools and science-based guidance to help them meet certification requirements and to evaluate their success at achieving biodiversity goals. As a starting point, landowners are mandated to address regulations for protecting significant landscape features (e.g., bald eagle nesting areas, deer wintering areas, or shoreland zones), but these regulations do not provide a comprehensive framework for conserving the full array of biodiversity. For example, forest planning efforts by landowners typically do not include strategies for conserving other key biodiversity elements (e.g., area-sensitive species or late-successional forest species). Further, landowners have traditionally applied existing planning tools independently. A common framework could enable land and wildlife managers to work across parcel boundaries to conserve biodiversity in managed forests.

Previous research funded through The Maine Cooperative Forestry Research Unit (CFRU) and others have generated the tools necessary for assessing important biodiversity values, positioning Maine to be a leader in biodiversity conservation on managed forestlands. Specifically, the CFRU has funded a number of projects that have resulted in development of *condition* indicators for managed forests in Maine (Hagan and Whitman 2006). Typical indicators of sustainable forestry certification programs only describe landowners' policies, practices, and institutional capacity to protect biodiversity. These *policy response* indicators reflect the implementation of certain policies and practices by a forest manager to protect a value, in this case biodiversity. While important, policy response indicators provide no information about the actual status of biodiversity (Hagan and Whitman 2006). Condition indicators are designed to directly quantify the status or current condition of representative elements of biodiversity and henceforth, are the focus of this report.

A number of indicators have been developed for commercial forestlands in Maine that address stand- or landscape-scale biodiversity values. At the stand-scale, for example, late-successional (>100 years old; LS) forest provides important structure (e.g., large trees, large snags, and large logs) associated with many species of lichens, mosses and liverworts in the Northeast (Selva 1994, Cleavitt 2009). Whitman and Hagan (2007) tested a suite of potential LS indicators for northern hardwood and spruce-fir forests in Maine and concluded that managers could use large (≥16 in dbh) tree density as an indicator of the degree to which a stand is in LS condition. This indicator can be used to assess the abundance of LS attributes so that maintenance of those conditions can be integrated into management decisions.

At the other end of the successional spectrum, early-successional (ES) habitats in New England are thought to have declined as forest succession has progressed following abandonment of agricultural lands previously afforested in 1700-1800's, and from changes associated with accelerating rates of conversion of forestlands to residential, suburban and urban uses during the mid 1900's to present. This decline in ES habitat has likely contributed to the decline of many "disturbance-dependent" birds, particularly neotropical migrants (Litvaitis 1993, Hunter et al. 2001). Researchers from Manomet Center for Conservation Sciences (Manomet) studied bird species in northern Maine and documented their relationships with habitats and habitat structure in managed and unmanaged stands. Their study indicated that total basal area (BA) was the single best predictor of the occurrence of ES birds (Hagan and Meehan 2002). Those results were subsequently used to develop ES bird indicators for managed forests (A. Whitman, Manomet Center for Conservation Sciences, *in preparation*).

To address the broader scale issues of landscape composition and configuration, landscape-scale indicators were developed for the Canada lynx and American marten, which are two wide-ranging flagship species occurring in northern and western Maine. Together, lynx and martens represent a range of ecological conditions (ES forest and mid- to LS forest, respectively) associated with habitat occupancy. These area-sensitive species have also been evaluated as umbrella species for biodiversity conservation in northern Maine, and their habitat requirements were found to encompass the requirements for >85% of the forest-generalist, deciduous-forest specialist, and coniferous-forest specialist vertebrate species (n = 111) occurring in northern Maine (Hepinstall and Harrison, Department of Wildlife Ecology, University of Maine, *in preparation*). Thus, rather than managing separately for the specific habitat needs of each species within a diverse forest community, landscape management can potentially be simplified to focus on a few species with habitat requirements that capture those of many other species.

Past CRFU-funded research has developed predictive models for lynx and martens. In summary, the probability of lynx occurrence in northern Maine had a strong positive association with snowshoe hare density and the proportion of mature conifer forest at the scale of a lynx home range (Simons 2009). Further, previous UMaine research identified conifer or mixed, advanced regenerating forest 15-35 years post harvest as the habitat type that supports the highest density of snowshoe hares in northern Maine (Fuller and Harrison 2005, Robinson 2006, Fuller et al. 2007, Scott 2009). Marten occurrence in northern Maine was best predicted by the amount of suitable habitat, where suitable habitat was defined as >6.7 ac (2.7 ha) patches of forest with >80 ft^2/ac (18 m^2/ha) BA of trees ≥3 in (7.6 cm) diameter and dominant tree height >30 ft (6m) (Chapin et al. 1998, Payer 1999, Payer and Harrison 2003, Payer and Harrison 2004, Fuller and

Harrison 2005). Spatially explicit modeling tools for martens and lynx developed based on this research provide tools for simplifying biodiversity planning at scales relevant to forest management decisions.

In 2006 we were funded by the CFRU to apply a suite of condition indicators developed for managed forests in Maine to an area that represents the diversity of forest management legacies, forest management regimes, and landowner types present in northern Maine. Our goals were to provide a better understanding of the performance of a set of stand- and landscape-scale biodiversity indicators, and to identify current and future challenges to planning and managing for biodiversity in commercially managed forests. Our objectives were to:

1) Map and quantify 9 stand- and landscape-scale biodiversity indicators and assess their variability across a diverse set of legacies, owner types and forest management regimes in northern Maine.

2) Evaluate the scalability and performance of the indicators to determine which of those desired conditions improve as one increases the scale of management from a single parcel to a multi-township scale.

3) Forecast and quantify change in the indicators based on three alternative forest management scenarios and evaluate conservation costs and benefits at scales ranging from 1-14 townships.

4) Quantify changes in sustainable harvest volume associated with biodiversity planning and alternatively, the changes in future biodiversity associated with a strategy of harvesting the maximum allowable sustainable volume of fiber.

STUDY AREA

We selected 14 townships in north-central Maine as the study area for this project, including: T4 R14 WELS, T4 R15 WELS, T5 R14 WELS, T5 R15 WELS, T6 R13 WELS, T6 R14 WELS, T6 R15 WELS, T7 R13 WELS, T7 R14 WELS, T7 R15 WELS, T7 R16 WELS, T8 R14 WELS, T8 R15 WELS, T8 R16 WELS (Figure 1). Those townships provided a representative sample of the variety of forest management legacies that have been created since the spruce budworm outbreak of the 1970s and 1980s within a large contiguous area (344,034 acres) of north-central Maine. The study area was comprised of 23 parcels held by 9 different landowners; parcels were defined as a contiguous land unit within the study area which was owned by a single entity. Parcels ranged in size from 2.6 to 111 km^2 and represented a mix of ownership types which included a non-profit organization, several large and small commercial landowners (with and without easement), and state-owned and managed lands. Data that were summarized by ownership included 1 or more parcels that were within the study area and owned by the same entity.

LAND COVER DATA

A single land-cover classification system was applied to the study area, which was based on forest harvest and composition information derived from medium-resolution (30 m pixel) satellite imagery (Legaard et al., Maine Image Analysis Laboratory, University of Maine, *in*

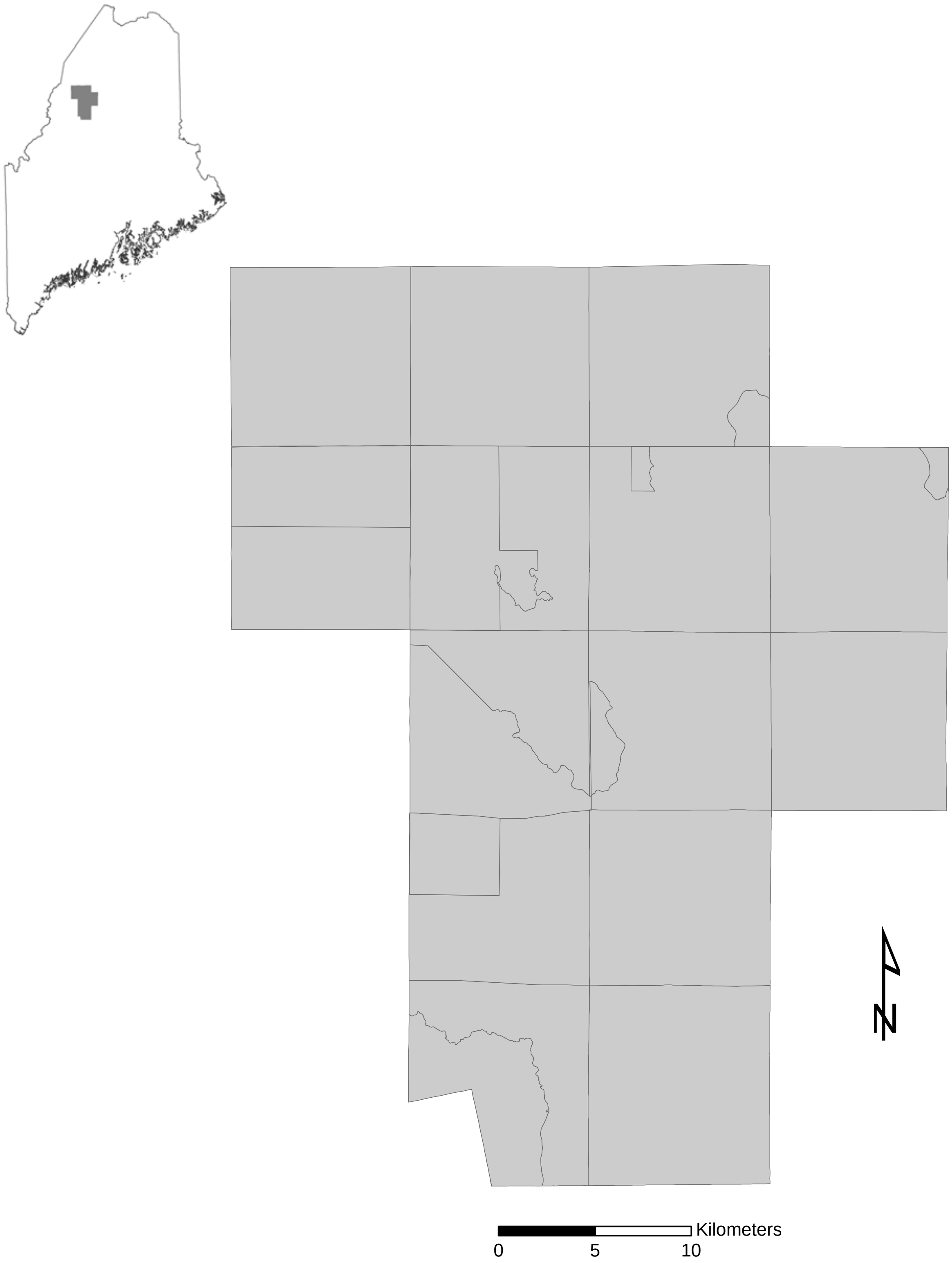


Figure 1. Study area in north-central Maine, U.S. A. showing township (n=14) and parcel (n=23) boundaries.

preparation) and FIA plot data. Forest harvest data were generated from Landsat satellite imagery from 1973-2007 based on vegetation indices (e.g., Normalized Difference Moisture Index) and image interpretation. Harvested areas 1988-2007 were classified into two classes (‘light’ and ‘heavy’) based on the magnitude of biomass change. “Light” harvest entries were interpreted as partial harvests or tending operations of the mature growing stock (e.g., selection harvests and first entry shelterwood harvests), and “heavy” harvest entries were interpreted as stand-replacing or regeneration harvests (e.g., clearcut harvests and overstory removals, and some heavy shelterwood harvests). Only heavy harvest entries were mapped 1973-1988. Generalized forest type information (i.e., softwood, mixedwood, hardwood) was based on the Maine Gap Vegetation and Landcover map (MEGAP) for unharvested areas and an unsupervised classification of a 2004 Landsat satellite image for harvested areas.

Forest harvest and composition data were spatially combined and used to delineate stands based on common harvest history and composition. Stand size ranged from 5 ac (2 ha) to 617 ac (250 ha). We used publically available Forest Inventory and Analysis (FIA) plot data (United States Department of Agriculture Forest Service 2007) to estimate distributions of tree stem size class, stocking density, and age associated with mid-to-late successional stands within the study area. FIA plots were selected from a ~4.0 million ac (~1.6 million ha) reference area (Simons 2009), which encompassed our study area, to provide sufficient data records for reasonable estimates of forest characteristics. We randomly assigned estimated characteristics to individual stands. For regenerating stands, age circa 2007 was estimated based on the number of years elapsed since “heavy” harvest. Size class and stocking density was estimated using the Forest Vegetation Simulator (FVS) (United States Department of Agriculture Forest Service 2002) and FIA plot data. In the final step of developing the map of forest vegetation characteristics for our study area, all stands were intersected with a parcel ownership map circa 2007.

METHODS

BIODIVERSITY INDICATORS FOR MANAGED LANDS IN NORTHERN MAINE

We analyzed nine indicators (Table 1) that were developed for northern Maine based on previous research conducted by University of Maine and Manomet. We included both stand- and landscape-scale indicators of early-successional (ES) forest and mid- to late-successional (LS) forest, which could be evaluated using the information typically available in existing GIS databases and supporting timber inventories. We used six stand-scale indicators to assess the forest structure of parcels. We also evaluated three landscape-scale indicators derived from spatially-explicit models developed for lynx and martens to understand the effects of forest composition and configuration on area-sensitive wildlife. For all of the nine condition indicators, our results are presented as the percent area estimated to have the habitat conditions deemed suitable for each condition (described below). This was done at four scales: parcel, township, 4-township unit, and the 14 township study area. Structural characteristics (e.g., basal area) were estimated using satellite-derived information and FIA plot data and were randomly allocated to stands. Our overall results should be considered representative of the forest patterns at all four scales. Data are, however, not intended for stand-specific interpretation, which would require extensive field surveys of stand-specific vegetation characteristics.

Table 1. Condition indicators of biodiversity for managed forestlands in northern Maine. Stand-scale indicators included are early-successional (ES) shrub bird habitat, ES sapling bird habitat, snowshoe hare habitat, marten habitat, late-successional northern hardwood forest, and LS spruce-fir forest. Landscape-scale indicators included are male and female marten occurrence and lynx occurrence.

Scale	Indicator	Definition
Stand		
	1A. ES shrub bird habitat	Percent of forestland with Basal Area (BA) <6 ft^2/ac
	1B. ES sapling bird habitat	Percent of forestland with BA <59 ft^2/ac
	1C. Snowshoe hare habitat	Percent of forestland with conifer or mixed, even-aged regenerating forest (15-35 years post harvest)
	2A. Marten habitat	Percent of forestland in patches ≥6.7 ac with BA ≥80 ft^2/ac and mean stand height ≥30 ft (for trees ≥3 in (7.6 cm) dbh) and with canopy closure >30%
	2B. LS northern hardwood	Percent of Hardwood-dominated forestland ≥100 years old with stand size class 4 and canopy closure ≥60%
	2C. LS spruce-fir	Percent of Softwood-dominated forestland ≥100 years old with stand size class 4 and canopy closure ≥60%
Landscape		
	3A. Male marten occurrence	Percent of forestland with ≥60% probability of occurrence for male martens
	3B. Female marten occurrence	Percent of forestland with ≥60% probability of occurrence for female martens
	4A. Lynx occurrence	Percent of forestland with ≥60% probability of occurrence for lynx

Stand-scale indicators

Indicators 1A and 1B: Early-successional shrub (ES Shrub) and sapling (ES sapling) bird habitats.

Populations of many bird species associated with early successional forest habitats are declining across the eastern U.S. as a result of succession following past afforestation and recent increases in forestland conversion to non-agricultural or forest uses (Hagan et al. 1997, Askins 2001, Gobster 2001, Brooks 2003, Litvaitis 2003). Timber harvesting typically sets back succession and thus can create habitats used by ES shrub- and sapling-associated bird guilds (Hagan et al. 1997). Thus we used structure-based condition indicators associated with the presence of ES bird species guilds from an existing dataset of bird-habitat relationships for northern Maine (Hagan and Meehan 2002). In a previous CFRU project, Manomet researchers used stepwise logistic regression to evaluate the ability of 12 habitat variables to predict the presence of birds associated with ES forest. They concluded that total BA (trees >7.6 cm dbh) best explained the presence of ES bird species based on point counts (Hagan and Whitman 2004). Using those data, they calculated two BA thresholds that represented inflection points above which a suite of species associated with either shrub stage (Mourning Warbler, Palm Warbler, Song Sparrow, Lincoln's Sparrow, and Alder Flycatcher) or sapling stage (White-throated Sparrow, Common Yellowthroat, Chestnut-sided Warbler, Nashville Warbler, and Chipping Sparrow) habitats were significantly less likely to be present (6 ft^2/ac and 59 ft^2/ac, respectively) (A. Whitman, Manomet Center for Conservation Sciences, *in preparation*). Regenerating forest stands with total BA $\leq$6 ft^2/ac (shrub habitat) and >6 ft^2/ac but $\leq$59 ft^2/ac basal area (sapling habitat) were identified and quantified at the 4 spatial scales of our analysis to index the percent of forestland in habitat suitable for ES guilds of forest birds.

Indicator 1C: Snowshoe hare habitat (Hare).

The snowshoe hare is considered a keystone species in the northern boreal forests of North America (Krebs et al. 2001) and are an important prey species for many carnivores, including the U.S. federally threatened Canada lynx. Lynx are specialist predators of hares (Koehler and Aubry 1994, Aubry et al. 2000), and because hare density can act as a regulating factor on lynx populations, the presence of habitat conditions that support high snowshoe hare densities is considered essential for lynx conservation in the U.S. (U.S. Department of Interior 2008). Previous research in Maine has clearly documented the close association between snowshoe hare density and the dense understory conditions of conifer-dominated regenerating clearcuts (Fuller and Harrison 2005, Robinson 2006, Fuller et al. 2007, Vashon et al. 2008b, Scott 2009). We identified softwood and mixed stands across our study area that had regenerated for 15-35 years circa. 2007 based on a time series of Landsat TM-derived satellite imagery (Simons 2009). We quantified those data across each of our 4 spatial scales of analysis to index the percent of forestland in high quality hare habitat (HARE).

Indicator 2A: Stand-scale marten habitat.

At the stand scale, martens select habitat types with complex physical structure because they provide protection from predators (Hargis and McCullough 1984, Hodgman et al. 1997), resting sites (Buskirk et al. 1989, Bull and Heater 2000), and access to prey (Sherburne and Bissonette 1994, Thompson and Curran 1995). Research in Maine has suggested that the minimum BA and height thresholds for a forest stand to become suitable habitat for adult, resident martens are 18 m^2/ha (80 ft^2/ac) and 9 m (30 ft), respectively, for trees $\geq$7.6 cm (3 in) diameter at breast height (dbh) (Payer 1999, Payer and Harrison 2003, Payer and Harrison 2004, Fuller and Harrison 2005), and that adult, resident martens did not use forest stands $\leq$2.7 ha (6.7 ac) in area (Chapin et al. 1998). We identified stands that met these conditions based on stand structural characteristics estimated from our Landsat time series and FIA information. We then quantified those conditions at each of our 4 spatial scales to calculate the percent of forestland suitable for stand-scale use by resident martens.

Indicators 2B and 2C: Late successional (LS) northern hardwood and LS spruce-fir stands.

Previous research in Maine has determined that large (≥16 in dbh) tree density is an indicator of LS conditions in northern hardwood and spruce-fir stands (Whitman and Hagan 2007). However, large tree density could not be estimated from the FIA plot data so we classified stands ≥100 years old and stand size class 4 (i.e., sawtimber) with canopy closure ≥60% as LS stands. Within the study area, we groundtruthed a random sample of 116 stands that we determined had potential LS condition based on satellite imagery. We concluded that 58% of the stands surveyed (n=116) were size class 4 and canopy closure ≥60%, and that 55% of those closed-canopy stands with sufficient size characteristics (n=67) actually contained LS conditions. Thus, only 32% of the 116 stands initially identified as having potential LS value based on remotely sensed information were field-verified to actually contain LS conditions. We identified hardwood-dominated and softwood-dominated stands that met our definition of LS and quantified across each of our 4 spatial scales of analysis to evaluate the percent of forestland in *potential* LS northern hardwood and LS spruce-fir condition. Based on our ground truth results, however, estimates of LS condition likely overestimated the true occurrence of LS conditions in this landscape.

Landscape-scale indicators

Indicators 3A and 3B: Probability of landscape-scale occurrence for resident male and female American martens.

Hepinstall et al. (University of Maine, *in preparation*) developed predictive models to evaluate the effects of habitat composition and habitat configuration on the occurrence of male and female martens at the scale of a marten home range based on long-term empirical data collected at The University of Maine (Katnik 1992, Payer 1999, Fuller and Harrison 2005). Results indicated that probability of marten occurrence was positively influenced by the amount of suitable habitat and was negatively influenced by an increase in patch density (females) or landscape shape index (males). We calculated those variables for our study area and used the predictive logistic regression models to derive probabilities of occurrence for male and female martens across our study area. We then identified all locations with ≥60% probability of occurrence for male or female martens and summarized those results across each of our 4 spatial scales of analysis. Results are presented as the percent of forestland at each scale that represented areas with ≥60% probability of home range scale occurrence for resident male and female martens.

Indicator 4A: Probability of landscape-scale occurrence for Canada lynx.

Northern Maine has been identified as essential to the conservation of lynx in the contiguous U.S. Previous research has also suggested that conserving areas that have a >50% probability of occurrence for lynx would benefit a number of other early-successional species (e.g., Yellow Warbler, American Woodcock, and Chestnut-sided warbler) (Hepinstall and Harrison, The University of Maine, *in preparation*). To provide a better understanding of the influence of composition, habitat patch configuration, and snowshoe hare density on lynx at the scale of a home range, Simons (2009) modeled lynx occurrence in northern Maine based on snow track surveys conducted by the Maine Department of Inland Fisheries and Wildlife. Simulated occupied (n = 18) and unoccupied (n = 25) home ranges were randomly located based on the lynx tracks recorded during the surveys. Results indicated that the probability of lynx occurrence was positively influenced by snowshoe hare density and the percent of mature conifer forest at the scale of the average 75% adaptive kernel home range area (Vashon et al. 2008a) of radio collared lynx in Maine (Simons 2009). As with the marten occurrence indicators, we identified all locations with ≥60% estimated probability of occurrence for lynx using our predictive logistic regression models. Results are presented as the percent of forestland across each of our 4 spatial scales that represented areas with ≥60% probability of home range scale occurrence for lynx.

RESULTS AND DISCUSSION

STATUS OF BIODIVERSITY INDICATORS WITHIN THE STUDY AREA

Percent of forest area within the 344,034 acre study area meeting conditions for the stand- and landscape-scale indicators ranged from <1% to 43% (Table 2). The indicators that require late regenerating conditions (ES sapling bird habitat, hare habitat, and lynx occurrence) were relatively well represented on the landscape and those conditions represented ≥18% of the forestland. Stands meeting the conditions for LS northern hardwood, LS spruce-fir, and ES shrub habitat were particularly sparse, collectively representing <5% of the landscape. These results suggest that stands supporting ES habitat for shrub-associated birds, LS value in northern hardwoods, and LS value in spruce-fir stands are uniformly rare across the landscape and should receive high conservation priority. Forestland able to support ≥60% probability of occurrence was the most limiting for female martens, with only 10% of the forestland in that condition. The area of forestland currently able to support ≥60% probability of occurrence for male martens was relatively greater (18%), but still low. These results suggest that although stand-scale marten habitat comprised the highest percent of forestland across all indicators (43%; Table 2), landscape-level habitat conditions for occupancy by martens were relatively uncommon. Further, our model assumptions about post-harvest structure following partial harvests likely resulted in an overestimate of the distribution of marten habitat ca. 2007. Recent ground surveys (Fuller and Harrison, University of Maine, *unpublished data*; Legaard and Sader, University of Maine, *unpublished data*) suggest that most partial harvests do not meet the residual BA and canopy closure requirements of martens. In contrast, our modeling results predicted that ~60% % of partial harvests would meet marten habitat requirements. We recommend further research to document the extent that residual stand conditions in partial harvests meet the habitat requirements of forest dependent wildlife.

A COMPARISON OF STAND- AND LANDSCAPE-SCALE BIODIVERSITY INDICATORS ACROSS PARCELS OWNED AND MANAGED BY DIFFERENT LANDOWNERS

For 3 of our 6 stand-scale condition indicators, we observed wide variation in the percent of forest area considered as suitable across the range of parcels owned and managed within our study area (Figure 2). Two of those indicators reflected late-regenerating conditions and had medians of intermediate value across the parcels (hare habitat = 13%; ES sapling bird habitat = 27%). The third indicator, marten habitat, had the widest distribution of all stand-scale condition indicators (range 15% - 87% of forestland) and the highest median (parcel-level median = 45%). We caution, however, that these results are influenced by model assumptions that may have

Table 2. Percent of forest area for the 344,034 acre study area meeting conditions for the stand- and landscape-scale indicators. Structural characteristics (e.g., basal area) were approximated based on a combination of satellite-derived information and FIA plot data for the 4.0 million ac (1.6 million ha) landscape encompassing our study area.

Stand		% Forestland
	1A. ES shrub bird habitat	3%
	1B. ES sapling bird habitat	32%
	1C. Snowshoe hare habitat	18%
	2A. Marten habitat	43%
	2B. LS northern hardwood	0.3%
	2C. LS spruce-fir	1.4%
Landscape		
	3A. Male marten occurrence	18%
	3B. Female marten occurrence	10%
	4A. Lynx occurrence	25%

overestimated suitable marten habitat conditions. In contrast, percent of forestland providing ES shrub bird habitat, LS northern hardwood, and LS spruce-fir had narrow distributions of values and the lowest medians across parcels (2%, 0.3% and 0.6% respectively). Thus, these 3 stands-scale indicators occur at particularly low levels within parcels (Figure 2) as wells as across all parcels (Table 2). The need for conservation strategies to conserve the remaining LS habitats is further emphasized by the fact that only ~32% of *potential* LS stands identified via remote sensing actually supported LS value according to results from our field verifications.

At the parcel-level, moderate to high (≥0.70) correlations (Table 3) were observed between ES sapling habitat for birds and hare habitat (0.98), between ES shrub habitat for birds and hare habitat (0.70) and between LS northern hardwood habitat and stand-scale marten habitat (0.70). This suggests that landowners may achieve multiple biodiversity objectives, particularly among ES forest bird habitat and hare habitat when practicing harvests that remove a high proportion of overstory trees. Based on lower correlations among mid- and late-successional condition metrics (range 0.04 – 0.70), separate management strategies may be required to maintain all mid- and late-successional values within a single ownership parcel (Table 3).

To determine if all parcels contributed value to at least one of the indicators, and to identify any parcels that contributed multiple biodiversity values, we ranked the parcels by each of the stand-scale indicators. Results indicated that the majority of parcels (61%) ranked in the 25th percentile for at least one of the indicators. Only one parcel provided moderate value (i.e., at or above median) for all stand-scale indicators. Two parcels ranked at or below the median across each of the six stand-scale biodiversity indices. Not surprisingly, parcels that ranked high for one of the early-successional indicators tended to rank low for the LS indicators or for marten habitat.

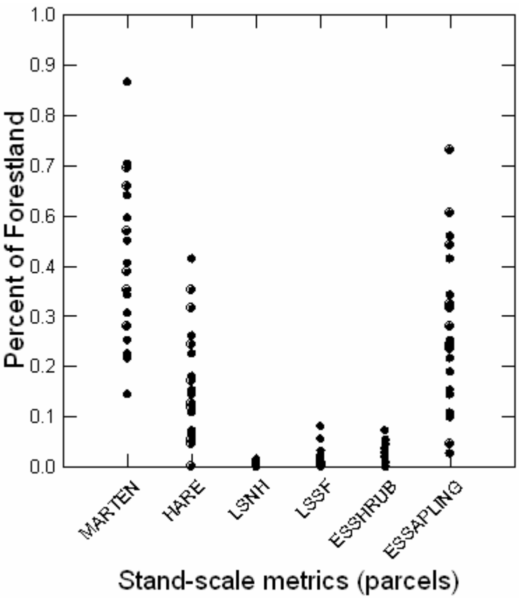


Figure 2. Distribution of stand-scale metrics across 23 parcels in northern Maine, including percent of forestland providing marten habitat (MARTEN), hare habitat (HARE), late-successional northern hardwood habitat (LSNH), late-successional spruce-fir habitat (LSSF), early-successional shrub habitat (ESSHRUB), or early-successional sapling habitat (ESSAPLING).

The distribution of values for each of the landscape-scale condition indicators was extremely wide and ranged from 0% to ≥80% across the 23 parcels for each of the 3 indicators (Figure 3). Across the study area, however, the percent forestland providing ≥60% probability of occurrence for lynx and for male and female martens was <25% (Table 2). Further, only 4 parcels had >40% of forestland suitable for lynx occupancy, 6 parcels had >40% of forestland suitable for occupancy by resident male martens, and only 2 parcels had >40% of forestland suitable for occupancy by resident female martens. Thus, although higher median values were observed when evaluating hare habitat and stand-scale marten habitat across parcels, only a few parcels provided the habitat conditions necessary to support landscape-scale occupancy by either lynx or resident martens. These results suggest that more attention needs to be directed at landscape composition and configuration, and that landscape conservation for lynx and martens needs to span across multiple ownerships.

We determined the percent of forestland providing ≥60% probability of occurrence for lynx across each of our 23 parcels. Parcels that ranked highly for lynx occupancy were in areas with large contiguous patches of high-quality hare habitat. These parcels had a history of clearcut harvesting in the 1970s and 1980s during the spruce budworm outbreak. Lynx require large home ranges [e.g., 75% adaptive kernel ranges for males and females were 20.7 mi^2 (53.6 km^2) and 9.9 mi^2 (25.7 km^2), respectively] (Vashon et al. 2008a); therefore, the *area* of forestland with ≥60% probability of occurrence would need to be considered by forest planners to ensure that the extensive area requirements of lynx could be achieved at the scale of an individual parcel. Four parcels in the study area were, however, smaller than the average home range area for a female lynx in northern Maine. Further, only 13 parcels were large enough to potentially support an individual male lynx, and of those parcels only six had sufficient forestland area with ≥60%

Table 3. Spearman's Rank Correlation Matrix comparing landscape-scale indicators to stand-scale indicators evaluated at the parcel-level, including ES shrub bird habitat (ES-Shrub); ES sapling bird habitat (ES-Sapling); hare habitat (Hare); stands-scale marten habitat (Marten); LS northern hardwood forest (LS-NH); and LS spruce-fir (LS-SF).

	ES-Shrub	ES-Sapling	Hare	Marten	LS-NH	LS-SF	Lynx ≥60%	Male Marten ≥60%
Lynx ≥60%	0.359	0.544	0.684	-0.552	-0.234	0.375		
Male Marten ≥60%	-0.583	-0.793	-0.736	0.968	0.464	0.014	-0.571	
Female Marten ≥60%	-0.497	-0.666	-0.604	0.908	0.277	-0.052	-0.504	0.928

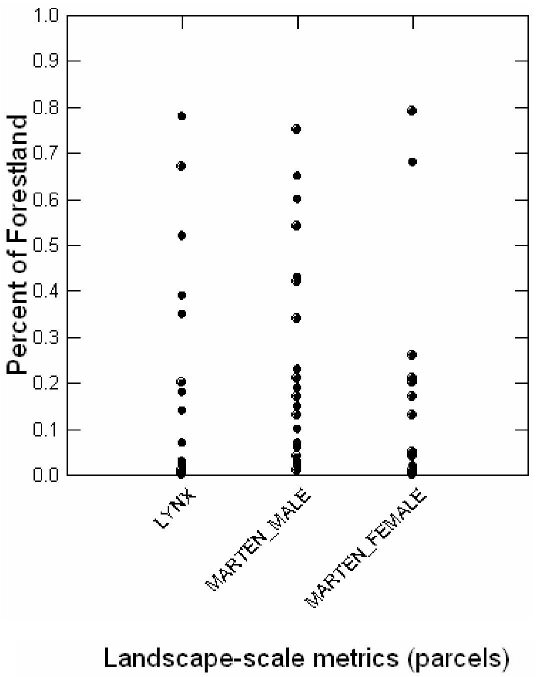


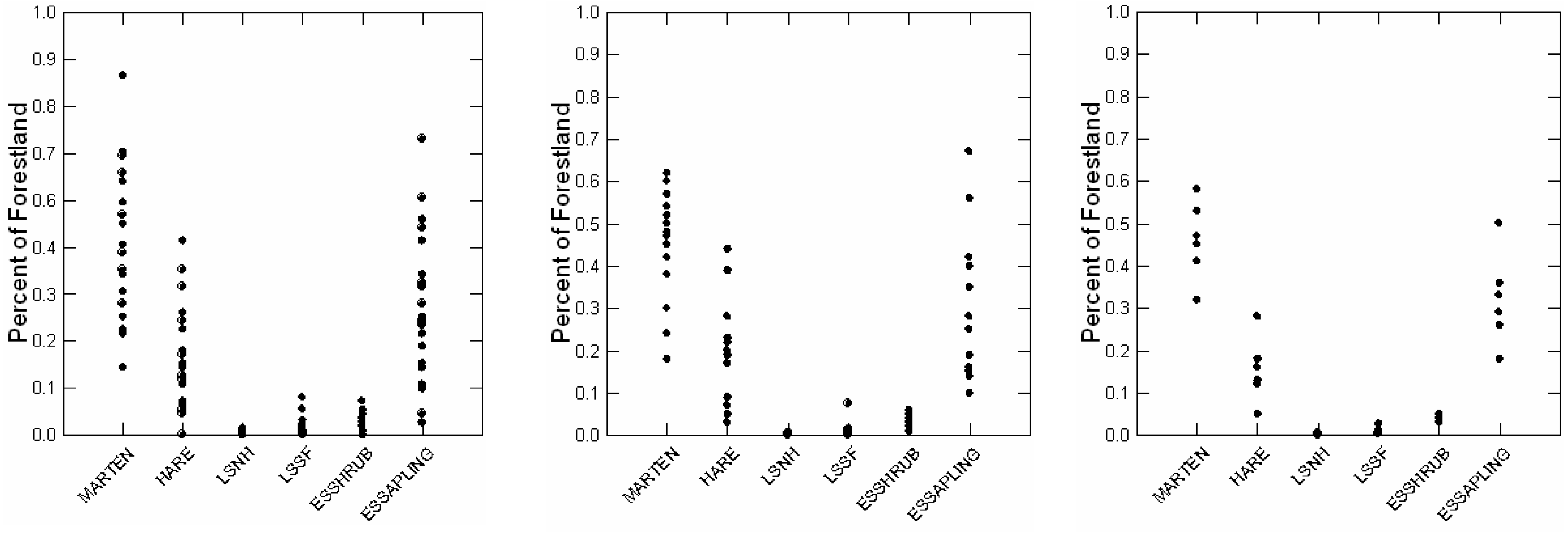
Figure 3. Distribution of landscape-scale metrics across 23 parcels in northern Maine, including percent of forestland providing ≥60% probability of occurrence for lynx, male martens, or female martens.

probability of occurrence to support a single resident male. Thus, these results strongly suggest that landscape planning for lynx will likely require cooperation across multiple landowners.

Parcels that ranked relatively high for marten occurrence were generally located in areas with relatively little past clearcutting or intensive partial harvesting (i.e., "heavy" harvests when classified by satellite imagery). Consequently, areas with ≥60% probability of occurrence for martens and lynx were negatively correlated (Table 3). Landscape-scale marten occurrence had a strong positive correlation with stand-scale marten habitat (Table 3). Median values associated with percent forestland providing ≥60% probability of occurrence for martens, however, were low (male median = 16% and female median = 5%) compared to the median value for stand-scale marten habitat (45%). These results suggest that although many parcels may have had a sufficient *amount* of habitat, habitat frequently occurred in fragmented patches, many of which do not provide the configuration requirements of martens. This fragmentation effect is likely exacerbated by the fact that many partial harvests may not meet the stand-scale habitat requirements of martens.

SCALABILITY OF BIODIVERSITY INDICATORS

We evaluated the *scalability* of the indicators at four spatial scales (parcel, township, four-township block, and 14 township study area) to determine if any of the indicators accrued as scale increased. Stand-level data were combined across parcel boundaries and township boundaries and compared to the original parcel-level results. Increasing the scale of analysis from parcels (Figure 4A) to townships (Figure 4B) had relatively little effect on the distribution of stand-scale indicators. In practice, the township is typically used as the functional unit for forest management planning, even within large, multi-township ownerships. Thus, this finding



A) Parcel

B) Township

C) 4-township blocks

Figure 4. Distribution of stand-scale metrics for 23 parcels in northern Maine at the parcel-level A) and aggregated by township B) and by 4 township blocks C), including percent of forestland providing marten habitat (MARTEN), hare habitat (HARE), late-successional northern hardwood habitat (LSNH), late-successional spruce-fir habitat (LSSF), early-successional shrub habitat (ESSHRUB), or early-successional sapling habitat (ESSAPLING).

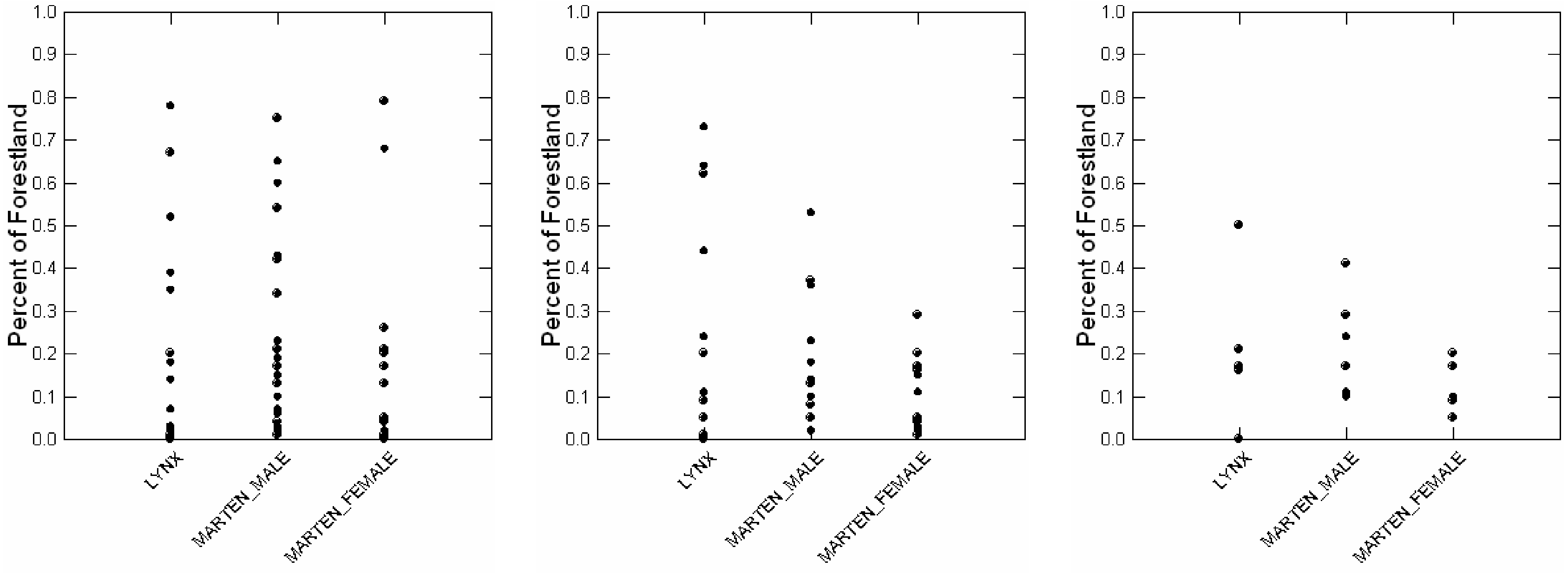
implies that the constraints for biodiversity conservation and management may be similar on both small and large individual ownerships. Increasing the scale to 4-township blocks (Figure 4C), however, noticeably decreased the range of variability in stand-scale condition indicators. There was, however, little effect on the median for any of the stand-scale indicators, indicating that, as represented by percent of forestland, the stand-scale condition of the landscape does not accrue in a monotonic fashion as spatial extent increases from parcel to township to 4-township block. Consequently, township and block values were represented by similar average values, regardless of scale, across the 6 stand-scale condition indicators that we evaluated.

Results suggested that scale was more important when evaluating biodiversity condition based on our landscape-scale condition indicators (Figure 5). Specifically, landscape-scale indicators were more sensitive to the location and configuration of the habitat defined by each aggregation of 4 townships (Figure 5C). Some 4-township blocks provided larger contiguous areas with ≥60% probability of occurrence, which is an important consideration because individual lynx(Vashon et al. 2008a) and martens (2007) are intrasexually territorial and require large home range areas in northern Maine. One 4-township area, which spanned 3 different owners, provided enough area with ≥60% probability of occurrence to support 7-9 resident adult lynx (approx. 2-2.6 lynx/100 km^2). A different but overlapping block of townships included the greatest concentration of area with ≥60% probability of occurrence for martens. This suggests that, abutting forestland owners may be able to strategically identify groups of townships that could potentially be managed to benefit both lynx and martens in landscapes with a diverse legacy of past forest management. Median values for the 4-township blocks were similar to the total percent forestland across the 14 townships for the landscape-scale indicators (Table 2). Thus, our results suggest that owners should consider 4 townships as the minimum scale appropriate to simultaneously manage for occurrence of both lynx and martens. Conservation planning for lynx and martens across considerably larger areas, however, could provide additional benefits because of the high degree of owner-to-owner variation in past forest management.

COMPARING PERFORMANCE ACROSS LANDOWNERS USING BIODIVERSITY INDICATORS

One potential application of biodiversity indicators is to evaluate landowner performance for purposes such as forest certification. Thus, we assessed and compared relative landowner performance on the basis of the stand-scale indicators, which our results indicated were relatively insensitive to changes in scale. The indicators for landscape-scale lynx and marten occurrence were more affected by spatial extent and, thus, were excluded from these analyses because area varied widely between ownerships (range 6 to 403 km^2). After calculating each of the stand-scale indicators at the ownership-level (n = 9), we ranked the landowners by indicator and compared the cumulative values to the parcel-level median. The results presented here should only be considered illustrative of the potential utility of condition indicators for evaluating or comparing landowners because stand characteristics for our study area were approximated rather than determined by ground-based inventory.

Landowners that performed well with respect to the early-successional indicators tended to perform poorly with respect to mid-late successional marten habitat. Stands supporting marten habitat were better represented in ownerships where partial harvesting has predominated and



A) Parcel

B) Township

C) 4-township blocks

Figure 5. Distribution of landscape-scale metrics across 23 parcels in northern Maine at the parcel-level A) and aggregated by township B) and by 4 township blocks C), including percent of forestland providing ≥60% probability of occurrence for lynx, male martens, or female martens.

Table 4. Spearman's Rank Correlation Matrix for stand-scale indicators evaluated at the ownership-level, including hare habitat (Hare); ES shrub bird habitat (ES-Shrub); ES sapling bird habitat (ES-Sapling); marten habitat (Marten); LS northern hardwood forest (LS-NH); and LS spruce-fir (LS-SF).

	Hare	ES-Shrub	ES-Sapling	Marten	LS-NH	LS-SF
Hare	1.000					
ES-Shrub	0.701	1.000				
ES-Sapling	0.983	0.675	1.000			
Marten	-0.962	-0.725	-0.962	1.000		
LS-NH	-0.714	-0.509	-0.672	0.696	1.000	
LS-SF	0.042	-0.150	0.092	0.168	0.008	1.000

little clearcut harvesting occurred; however, we reiterate our caveat that our modeling assumptions about post-harvest structure following partial harvest may have resulted in an overestimate of marten habitat. In contrast, early-successional indicators were generally well represented on ownerships with a past legacy of salvage logging during the spruce budworm outbreak of the 1970s and 1980s. Further, early-successional indicators were highly correlated at the ownership-level, and correlations between marten habitat and the early-successional indicators were all strongly negative (range -0.73 to -0.96; Table 4). Forestland on four of the ownerships had conditions for each of the early-successional indicators that had a cumulative area equal to or greater than the median observed across all 23 parcels. Hare habitat and ES sapling bird habitat were relatively well represented at the scale of the ownership (20-50% of forestland area), but ES habitat for shrubland associated birds was poorly represented (≤5%). This result indicates that ES Shrub habitats are not being created at a large scale using current forest management approaches and that the guild of wildlife species associated with shrub-stage habitats may be expected to decline under the forest practices that currently predominate in the commercially harvested landscapes of northern Maine.

Results for the LS indicators were more difficult to evaluate in terms of individual landowner performance. Two ownerships ranked low with respect to both LS northern hardwood and LS spruce-fir; both ownerships had a history of salvage logging and also ranked low in marten habitat (7th rank and 9th rank of 9 landowners) and high across all early-successional indicators (i.e., within the top 4 ranks for each of the 3 ES condition indicators). Two other ownerships, however, ranked low in LS spruce-fir habitat (7th and 9th) but high in LS northern hardwood habitat (1st and 2nd ranks) and generally low across all early-successional indicators. The ownership-level distribution of LS northern hardwood stands was positively associated with marten habitat; however, LS northern hardwood habitat was negatively correlated with the early-successional indicators (Table 3). Correlations between LS spruce-fir and other indicators were generally weak and LS spruce-fir habitat was only weakly positively correlated with marten habitat. Thus, condition indicators for the three early-successional habitats were generally highly correlated for the 9 ownerships (Table 3) and suggest that management for all three ES values can likely be achieved on a single parcel or ownership when stand replacing forms of management predominate. However, LS values will be more difficult to achieve and will require condition-specific management attention. Our results suggest that forest and wildlife managers will be challenged to provide habitat for all species on a single ownership or at scales of less than 4 townships. Further, we observed that ES shrub habitat, LS northern hardwood habitat, and LS spruce-fir habitat are already exceedingly rare across the parcels that we studied and will require special management attention if those conditions are to be maintained or improved in the future.

FORECASTING CHANGE IN BIODIVERSITY INDICATORS, 2007-2032, UNDER ALTERNATIVE FOREST MANAGEMENT SCENARIOS

We developed alternative forest management scenarios for the 14 townships to assess likely future trends in the 9 condition indicators and to provide a better understanding of the effect of forest management on biodiversity in northern Maine. Using the Remsoft Spatial Planning System we modeled three scenarios, 1) natural succession (NATRL); 2) continuing recent forest management trends for included ownerships (ASIS); and 3) maximize sustainable harvest (MAX). The Remsoft software supports both strategic forest planning using the program Woodstock and tactical harvest-block scheduling and layout using the program Stanley. The strategic objective for the two harvest scenarios was to maximize volume subject to even-flow harvest and ending inventory constraints while maintaining 95% growing stock over a 100-year planning horizon. Additionally, the baseline scenario (ASIS) was designed to project recent ownership-level harvest rate trends (2001-2007) and the effects of current forestry regulations (12 MRSA §8867-A to §8888 & MFS Rules Chapter 20), while still maintaining the overall strategic objective. Although the scenario to maximize sustainable volume also incorporated current forestry regulations (e.g., maximum clearcut size = 250 ac), it was not constrained to the current rates associated with different harvesting strategies (e.g., proportion of acreage clearcut vs. partially harvested) because those outcomes are not required via externally mandated standards or legislation.

We compared the change in percent of forestland in a suitable habitat condition for each of the 9 condition indicators under the scenarios projected over the period 2007-2032 (Figures 6 and 7). Results indicated that stand-scale indicators for early-successional habitats (Figure 6, panels 1A, 1B, and 1C) and LS habitats (Figure 6, panels 2B and 2C) will decline below current levels if current harvesting rates and patterns persist. Because of the importance of hare habitat to lynx, the area with probability of occurrence ≥60% for lynx will also decline under the baseline scenario (Figure 7, panel 3C). Stand-scale marten habitat (Figure 6, panel 2A) and landscape-scale probability of occurrence for male and female martens (Figure 7, panels 3A, 3B) will remain relatively stable under this scenario. It is important to note that these trends are largely dependent on the details of the growth models and distributions of post-harvest structure used during simulation (Simons 2009). Based on our models, regenerating forest that resulted from the salvage operations during the last spruce budworm outbreak would begin to acquire characteristics associated with marten habitat use in 2022, which may prove to be overly optimistic because field studies have indicated that the sapling stage may persist longer in some areas (Scott 2009) and that the natural stem exclusion process may be delayed relative to model assumptions.

If harvesting were to stop altogether (NATRL), early-successional habitats (Figure 6, panels 1A, 1B, 1C) are projected to decline, LS habitats would be expected to increase (Figure 6, panels 2B, 2C) and stand-scale marten habitat would increase (Figure 6, panel 2A). Most strikingly, the area with probabilities of occurrence ≥60% for male and female martens (Figure 7, panels 3A, 3B) would increase substantially under that scenario. In contrast, the area with probability of

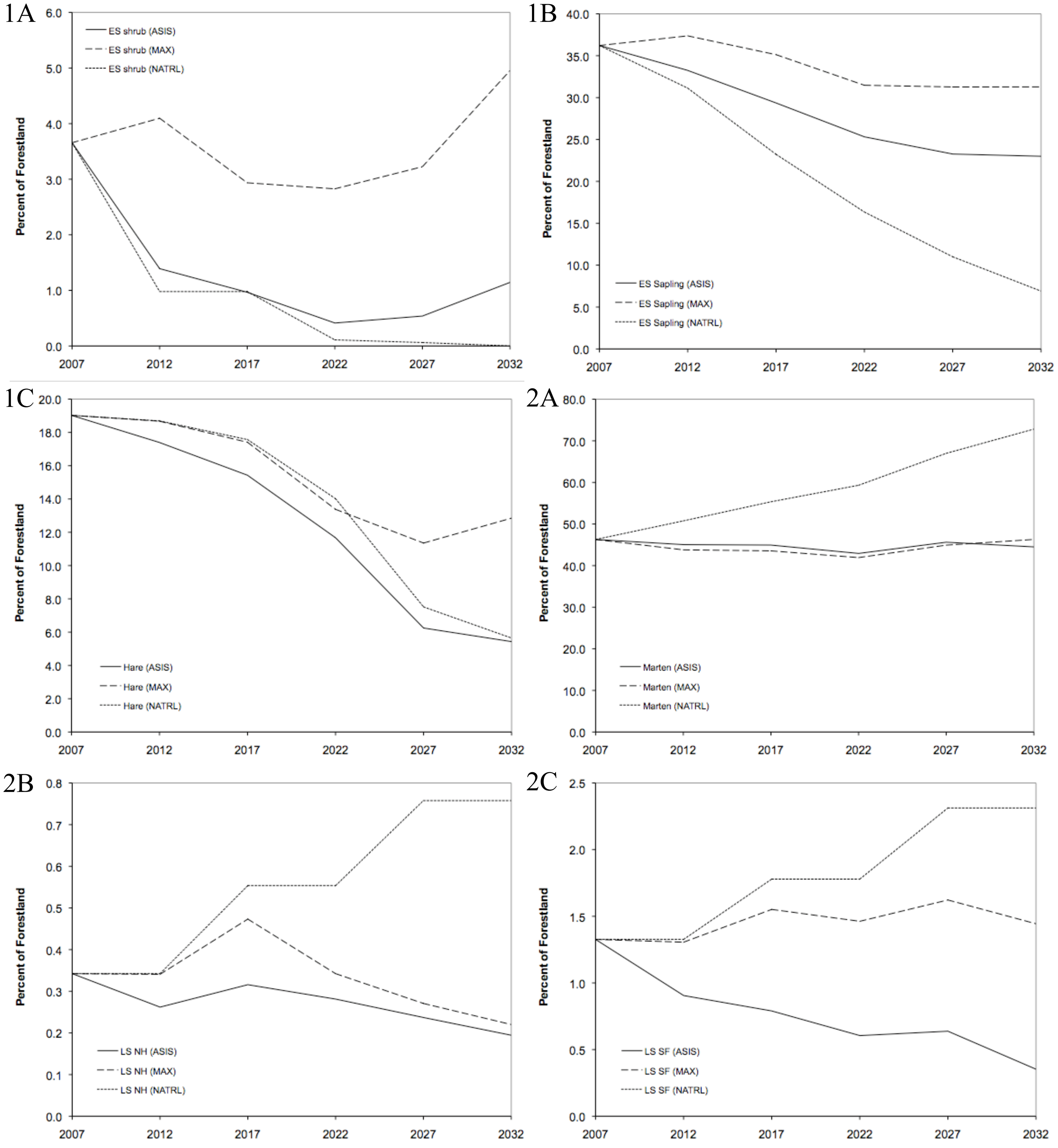


Figure 6. Projected trends, 2007-2032, in the percent of forestland across 23 parcels in northern Maine for each of the stand-scale metrics, including 1A) ES shrub bird habitat; 1B) ES sapling bird habitat; 1C) hare habitat; 2A) marten habitat; 2B) LS northern hardwood forest; and 2C) LS spruce-fir, under the scenarios natural succession (dotted line); continuation of recent harvesting trends (solid line); and maximize sustainable harvest (dashed line).

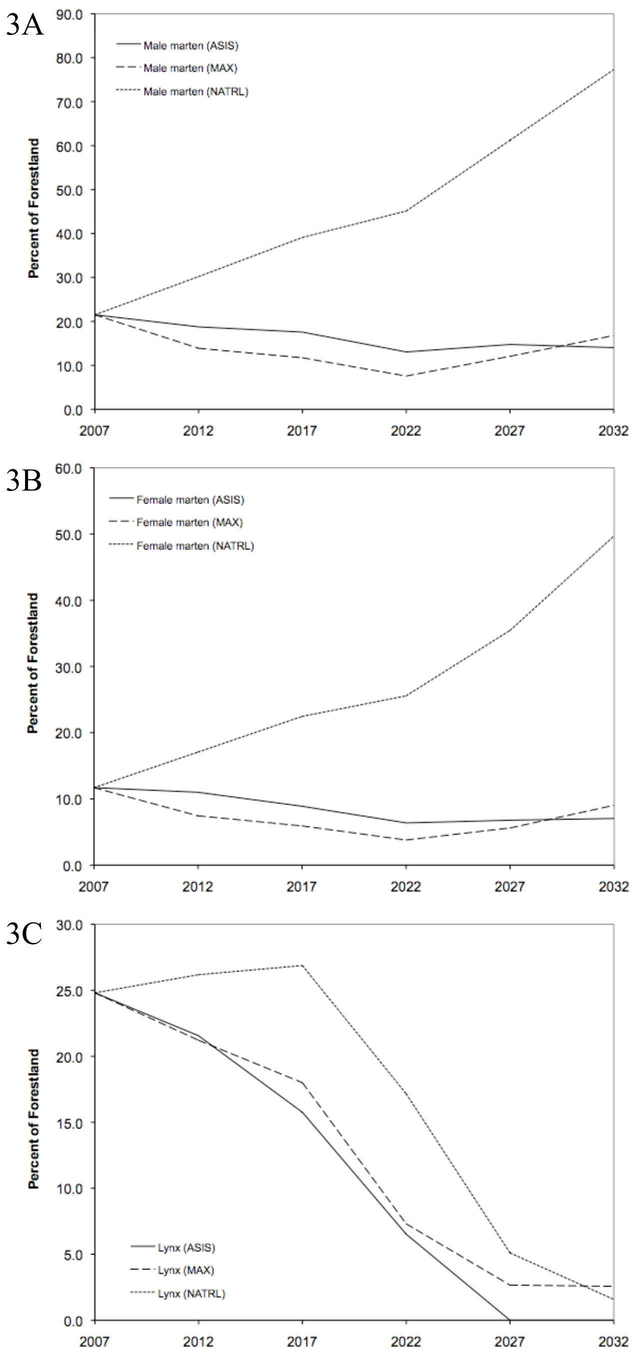


Figure 7. Projected trends, 2007-2032, in the percent of forestland across 23 parcels in northern Maine for each of the landscape-scale metrics, including area with probability of occurrence ≥60% for 3A) male martens; 3B) female martens; and 3C) lynx, under the scenarios natural succession (dotted line); continuation of recent trends (solid line); and maximize sustainable harvest (dashed line).

occurrence ≥60% for lynx (Figure 7, panel 3C) would also increase to 2019, but then would decline drastically to 2032 (Figure 6, panel 1C) in the absence of new overstory removals, which would be needed to stimulate the creation of additional hare habitat.

Results were highly variable under the scenario to maximize sustainable volume (MAX). ES shrub bird habitat and hare habitat would be projected to decline initially (Figure 6, panels 1A and 1C), but are projected to increase starting in 2013-2014, and to continue increasing until ~2027. Those trends were projected to reverse about 2028, because the higher rate of clearcutting associated with this scenario (Simons 2009) would stimulate the production of new early-successional habitat. This would also contribute to a delay in the initiation of decline in lynx populations from 2007 (ASIS and NATRL scenarios) to 2019 under the maximizing sustainable harvest scenario (Figure 7, panel 3C). Habitat supply for lynx is projected to decline precipitously under all 3 scenarios during the period 2019 to 2032. In contrast, ES sapling bird habitat is projected to remain relatively stable 2007-2032 under the MAX scenario (Figure 6, panel 2A). LS spruce-fir habitat is expected to fare better under the MAX scenario compared to the ASIS scenario (Figure 6, panel 2C), presumably because of a reduced emphasis on partial harvesting in mature softwood forest and an increase in clearcutting (Simons 2009). Area in LS northern hardwood stand condition is, however, expected to decline below the already extremely low levels documented in 2007 (i.e. potential LS stands represent only 0.35% of the landscape in 2007) under both the MAX and ASIS scenarios (Figure 6, panel 2B). The trends in marten habitat and area with probability of occurrence ≥60% for male and female martens are very similar between the ASIS and MAX scenarios (Figure 7, panels 3A, 3B). The percentage of the study area representing predicted areas of marten habitat occupancy is substantially reduced from levels observed in the 1970's-1990's (Simons 2009), and would not recover unless all harvesting is curtailed (i.e., NATRL scenario).

In addition to providing some benefit to ES and LS spruce-fir habitats, shifting to a strategy to maximize sustainable volume would provide additional volume and a reduction in annual acreage harvested (Simons 2009). Across the study area 11% more volume was allocated for harvest under the MAX scenario (145,547,337 ft^3 vs. 130,858,424 ft^3) compared to the ASIS scenario. The additional volume that is gained by shifting towards a scenario to maximize sustainable volume, which involves fewer acres partially harvested and more acres clearcut (Simons 2009), could provide an important starting point for landowners to consider putting additional acreage into set-asides without reducing harvest volumes. These set-asides could be used to conserve remaining LS habitats, to address habitat configuration requirements for marten, or to promote ES shrub habitat. Additionally, if reserved areas were placed in mature conifer forest, LS spruce-fir habitat, marten habitat, and deer wintering habitat would all be benefited by the same area. Thus, our results suggest that a shift in forest management strategy could benefit both landowners and biodiversity.

SUMMARY

Biodiversity indicators can provide landowners with valuable tools for simplifying conservation planning, evaluating the effectiveness of biodiversity management, and evaluating the relative efficacy of alternative management scenarios. Previous research funded by CFRU and others, and conducted by The University of Maine and Manomet, has positioned Maine to be a leader in developing methods to assess and monitor biodiversity on managed forestlands. Those previous projects developed a suite of *condition* indicators at the stand- and landscape-scale (Table 1), which were designed to assess the status of biodiversity. Those indicators contrast with the typical indicators of certification programs, which only describe landowners' policies, practices, and institutional capacity to protect biodiversity, but which provide no information about the actual status of biodiversity *per se*. Our analysis included six stand-scale indicators for assessing the presence and relative distribution of important successional stages (early, mid, and late) across a diverse set of owners, owner types and forest management regimes in northern Maine. Additionally, we evaluated three landscape-scale indicators derived from spatially-explicit models developed for Canada lynx (Simons 2009) and American martens (Hepinstall et al., University of Maine, *in preparation*). An analysis of landscape *condition* based on those two species enhanced our understanding of effects of forest composition and configuration on their habitat supply and also provided inferences about landscape condition for the 85% of sympatric forest vertebrates species represented under their broad-scale habitat umbrella.

The distribution of indicator values varied widely across the 23 parcels included in our study area, which formed a contiguous 14 township study area (344,034 acres) in north-central Maine (Figure 1). At the stand-scale, early-successional habitat associated with presence of shrubland birds (ES Shrub) and late-successional northern hardwood (LS NH) and spruce-fir (LS SF) stands all were particularly rare across the study area and exhibited a narrow range of variation across parcels. Our analyses indicate that these rare habitat conditions are not generally being managed for under the current regulations and predominant forest practices of northern Maine. The other stand-scale ES indicator, hare habitat, was relatively common at the parcel-scale; however, landscape scale habitat (≥60% probability of occurrence) for lynx was widely variable and represented a median of only 2.5% of area across parcels. Given that lynx are strongly associated with snowshoe hare density (Robinson 2006, Fuller et al. 2007, Vashon et al. 2008b, Simons 2009) at stand- and landscape-scales, our data suggest that distribution and configuration of high density snowshoe hare habitat is suboptimal for promoting lynx occurrence.

Similarly, marten habitat was well represented at the stand-scale, but landscape-scale occurrence of male and female martens was estimated to comprise a median of only 16% and 5% of the area, respectively, across the 23 parcels that we evaluated. We observed lower median values for occurrence of female marten relative to male martens, despite the smaller home range area of females (Payer 1999, Hearn 2007), which suggests that requirements for an aggregated configuration of suitable habitat by female martens may be especially difficult to achieve in managed landscapes without directed conservation planning. Further, our estimates of habitat supply for martens are likely overly optimistic because distributions of post-harvest structure following partial harvest used during modeling tended to assume greater residual BA and canopy cover than recent ground surveys would indicate in partially-harvested stands.

The effect of scale was a more important consideration for our landscape-scale condition indicators than for our stand-scale indicators. Increasing the scale of analysis from parcels to townships to 4-township blocks had relatively little effect on the stand-scale indicators (Figure 4). In contrast, landscape-scale indicators were more sensitive to the location of a 4-township block and the size of the contiguous area with ≥60% probability of occurrence it provided. Thus, the parcel-level may be sufficient when managing forest to meet the conditions associated with a stand-scale indicator, but owners should consider 4 townships as the minimum scale when managing for the occurrence of area-sensitive species such as lynx and martens. Lynx in particular require large home ranges relative to the size of parcels in northern Maine [20.7 mi^2 (53.6 km^2) for males and 9.9 mi^2 (25.7 km^2) for females] (Vashon et al. 2008a). Notably, only six of the 23 parcels included in our study area had sufficient forestland area with ≥60% probability of lynx occurrence to support an individual male lynx.

When evaluating the representation of stand-scale indicators across 9 different ownerships, it was evident that results were strongly influenced by past forest management history. Thus, ES indicators were highly correlated (Table 2) and were well represented on ownerships with a history of salvage logging during the spruce budworm outbreak of the 1970s and 1980s. Marten habitat was, however, not well represented on those ownerships. Instead, marten habitat was most prevalent where past forest management has occurred as partial harvesting, which is somewhat problematic given that previous research in northern Maine has provided equivocal results regarding the suitability of partially-harvested stands to martens (Fuller and Harrison 2005). Marten habitat was moderately (0.70) correlated with LS northern hardwood condition, but was weakly correlated with LS spruce-fir habitat. Generally, correlations between LS spruce-fir and the other indicators were weak, suggesting that maintenance of LS spruce-fir conditions will require specific management prescriptions. Consequently, because of negative and/or weak correlations between indicators, forest and wildlife managers will face significant challenges when attempting to manage for all biodiversity conditions on a single parcel or across large ownerships where the single township is the operational management unit.

To provide a better understanding of future biodiversity challenges, we projected the trend in each of the indicators, 2007-2032, under three alternative forest management scenarios. Results indicated that all 9 condition indicators declined an average of 52% under the scenario where current harvesting rates and patterns persist into the future (ASIS; Figures 7 and 8). It is important to note, however, that the timing of these trends is dependent on the details of the growth models used during simulation (Simons 2009). If harvesting were to immediately shift towards a strategy to maximize sustainable volume, 6 of the 9 indicators would decline by an average of 36%. Total area harvested under that strategy would likely be reduced, however, because of increased clearcutting (Simons 2009), which could provide enhanced opportunities for marten habitat and LS management. Additionally, 11% additional harvest volume (14,700,000 ft^3) could be realized across the ownerships. That additional volume could potentially be used to mitigate costs of creating set-asides for LS conditions, to promote landscape-scale marten conservation, or to promote shrubland habitats, without reducing harvest volumes below current levels. Hare habitat and lynx occurrence are projected to decline under all scenarios as habitat created during the salvage logging period continues to age and snowshoe hare densities begin to decline (Simons 2009). Nonetheless, increased reliance on clearcutting and herbiciding to promote spruce-fir regeneration would benefit lynx in the future (Simons 2009). Not surprisingly, if harvesting were to stop altogether (NATRL; Figures 7 and 8) all ES indicators, including lynx occurrence, are projected to decline. The LS indicators and marten indicators would increase during the period 2007-2032, by a striking 259% and 325% in the case of the male and female landscape-scale marten indicators.

MANAGEMENT IMPLICATIONS

Our analysis clearly demonstrated that the distribution of indicators is largely determined by the past forest management legacy of parcels or ownerships. ES habitats were well represented on parcels with a history of salvage logging during the budworm outbreak of the 1970s and 1980s. Thus, we recommend that stand-scale management for biodiversity on these parcels should be directed at maintaining the limited and declining supply of marten habitat and LS forest. At the same time, forest managers will need to plan to create a future supply of ES habitats, which are otherwise projected to decline as a result of broad-scale changes in forest management. Balancing these two objectives, ES and mid-successional/LS habitats, may require more harvesting using complete overstory removals, reducing annual harvest area, longer rotations in unharvested areas, and set asides for future LS conditions relative to current harvesting practices. A shift towards increased use of clearcut harvesting would also benefit lynx; areas that currently support a high probability of occurrence for lynx occur on parcels that historically experienced high rates of salvage harvesting, which have contributed to high snowshoe hare densities in these areas. Our modeling suggests that this could potentially be achieved across the entire study area without a reduction below current harvest volumes.

Parcels with a legacy of partial harvesting provided less ES habitat than parcels with a legacy of clearcutting. The large footprint of partial harvesting has also made LS habitats rare or uncommon. Stand-scale marten habitat and predicted landscape-scale occurrence for martens was generally greater on parcels with a partial harvest legacy. However, partial harvesting in northern Maine may not provide suitable habitat for martens as structural characteristics required by marten were not present on many of the partially-harvested sites that were measured on the ground (Fuller and Harrison, University of Maine, *unpublished data*). Moreover, our model assumptions likely resulted in an overestimate of marten habitat. Thus, we recommend increasing the area in stand-replacing harvests, reducing annual area harvested, paying more attention to residual stand and landscape conditions for martens and other forest wildlife, and increasing set-asides for LS habitat in areas dominated by a partial harvesting legacy. Our results suggest that moving to a strategy to maximize harvest volume could benefit landowners by increasing harvest volume, which could offset individual landowners' costs for conserving habitat for martens and LS species. Such a change would require a change in management philosophy and would require increased use of complete overstory removals.

Forest and wildlife managers must pay close attention to scale when planning for lynx and martens. We recommend that landowners consider four townships as the minimum scale for managing for lynx because few individual parcels or townships are likely to have sufficient area with ≥60% probability of occurrence for lynx. Similarly, landowners will likely find it necessary to look beyond a single parcel in order to meet habitat configuration requirements for martens. Thus, we recommend that abutting forestland owners strategically identify groups of ≥4 townships and work together to manage for the benefit of both lynx and martens.

Finally, we present an important caveat to our findings. Structural characteristics were estimated based on satellite-derived information and FIA plot data, and our results are representative of the general stand- and landscape-level patterns within the study area. Interpretations that require spatially-explicit characterization for particular stands should be viewed with caution, however, because of the limitations of the input data.

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